8 TeV ZZ Cross Section Measurement

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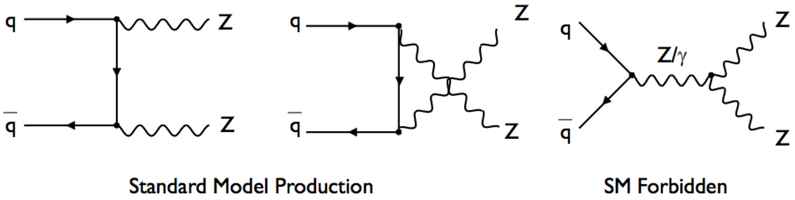
Introduction

- Measured the $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ cross section in 5.8 fb^{-1} of 8 TeV data.
- $\ell = e$ or μ, where ℓ comes either from $Z \to \ell^+\ell^-$ or the decay of a τ from $Z \to \tau^+\tau^-$.
- Measured in both an experimentally accessible fiducial volume and extrapolated to the total phase space.
- CONF Note: ATLAS-CONF-2012-090 (https://cdsweb.cern.ch/record/1460409)
- Support Document (restricted to ATLAS): ATL-COM-PHYS-2012-772 (https://cdsweb.cern.ch/record/1454147)
- Thanks to my co-editor Nick Edwards and the SM ZZ analysis team for their work in getting this result in time to support the Higgs result at ICHEP.

Overview

- Motivation
- Analysis Strategy
- ATLAS Detector
- Trigger/Data Acquisition
- Event Reconstruction
- Monte Carlo Simulation
- Event Selection
- Background Estimation
- Systematic Uncertainties
- Kinematic Distributions
- Cross Section Measurement

Motivation



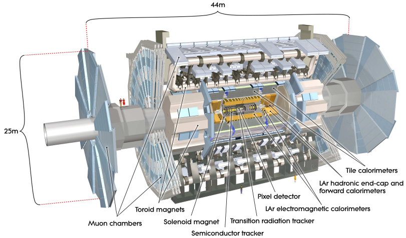
- Want to test Standard Model (SM) predictions at new high-energy frontier!
- Precise measurement of SM ZZ production is an important test of SM electroweak theory.
- Plan to eventually set limits on the SM forbidden production mechanism.
- Four-lepton signature is the "golden channel" for many searches, in which SM ZZ production is the major background.

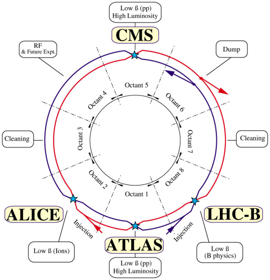
Analysis Strategy

- Want to measure ZZ production cross section.
- Identify ZZ candidate events in pp collision data:
  1. Detect leptons produced in the hard-scattering process.
  2. Identify opposite-sign, same-flavor lepton pairs.
  3. Use them to reconstruct Z-bosons and thereby identify candidates.
- Estimate background using the data-driven fake-factor method.
- Relate observed signal yield to production cross section using Monte Carlo (MC) simulation.
- Fit the production cross section using the maximum likelihood method.

ATLAS and the LHC

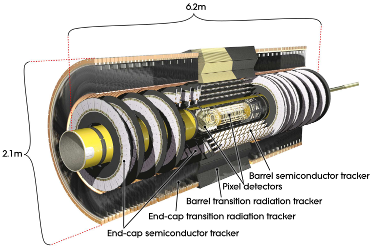
- A Toroidal LHC ApparatuS (ATLAS) detector at Large Hadron Collider (LHC).
- Used to study proton-proton collisions.
- Consists of four main parts:
  - Inner Detector (ID)
  - Calorimeters
  - Muon Spectrometer (MS)
  - Magnets





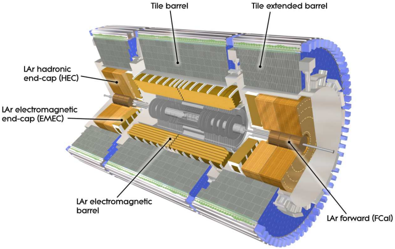
ATLAS: Inner Detector

- Charged particle tracking detector.
- Covers region: $|\eta| < 2.5$.
- Consists of three main parts:
  - Silicon pixel detector
  - Silicon strip detector (SCT)
  - Straw-tube detector (TRT)
- Includes diamond detector (BCM) in forward region, used to measure luminosity.



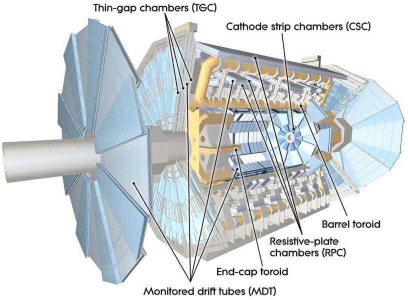
ATLAS: Calorimeter System

- Uses two types of active material:
  - Liquid argon (LAr)
  - Scintillating tile
- Covers region: $|\eta| < 4.9$.
- Consists of three calorimeters:
  - EM (LAr)
  - Hadronic (LAr & Tile)
  - Forward (LAr)



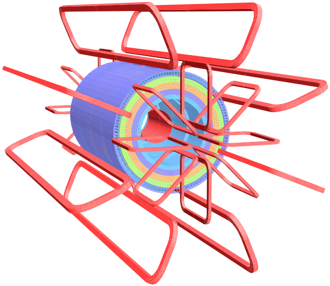
ATLAS: Muon Spectrometer

- Charged particle tracking detector.
- Covers region: $|\eta| < 2.7$.
- Composed of three layers of precision chambers, made from:
  - Drift-tubes (MDT)
  - Multi-wire proportional chambers (CSC)
- Multiple layers adjacent to the precision layers, used for triggering, made from:
  - Resistive plate chambers (RPC)
  - Multi-wire proportional chambers (TGC)



ATLAS: Magnets

- Two magnets:
  - ~ 2 T solenoid: surrounding the ID
  - $\sim 0.5 - 1$ T toroid: surrounded by the MS
- Solenoid bends charged particles in ϕ
- Toroid bends charged particles in η



Trigger & Data Acquisition

- LHC produces collisions for ATLAS with 50 ns period (20 MHz event rate).
- ATLAS uses three-level trigger (L1, L2, and EF) to select only $\sim$500 Hz to record.
- At each level, select events by looking for a high-p_{T} (> 24 GeV) lepton (e or μ) isolated from other charged particle activity.
- Electrons are required to have deposited less energy in hadronic calorimeters for L1 trigger.

Reconstruction

- Inner Detector:
  - Fit ID tracks starting with three silicon (pixel+strip) hits and extending them in helix through solenoid field to find additional hits before fitting the helix.
  - Fit vertices by combining tracks whose extrapolations to the beam line are close together; define new vertex when a track is more than 7σ away.
  - Primary vertex (PV) has highest $\sum_{\text{tracks}} p_{\text{T}}^2$.
- Calorimeters:
  - Define EM calorimeter clusters by using fixed window to scan through calorimeter cells to find those that have significant energy, defining the barycenter of each deposition as a precluster, and then defining the EM cluster as a fixed window around the precluster.

Reconstruction (ctd.)

- Muon Spectrometer:
  - Fit straight-line track segments in each layer using hits from precision chambers plus hits from adjacent trigger chambers.
  - Fit muon tracks by combining track segements from different precision layers in path through toroid field.
- Leptons:
  - Define electrons by combining ID tracks with EM clusters.
  - Define muons by combining ID tracks and MS tracks (or segments not included in tracks for muons used to reconstruct Z-bosons).

Monte Carlo Simulation

- Want to translate SM cross section into expected event yield.
- Use Monte Carlo generators to simulate $pp \rightarrow ZZ$+X$\rightarrow \ell^+\ell^-\ell'^+\ell'^-$+X and detector response.
- Simulation of quark annihilation process $q\bar{q} \rightarrow ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ done in six steps:
  - Parton distribution function (PDF) - internal structure of interacting protons: CT10
  - Matrix element (ME) - hard scattering interaction: PowhegBox
  - Underlying event (UE) - remainder of interaction between colliding protons: Pythia8
  - Parton shower (PS) - initial/final state radiation (due to both QED and QCD processes), hadronization, and decays into stable particles: Pythia8
  - PS revision - τ-lepton decays and hard ($p_{\mathrm{T}} > 20$ GeV) final state photon radiation simulated by Pythia8 & Photos respectively
  - Detector simulation - simulation of the interactions with detector: Geant4
- Gluon fusion process $gg \rightarrow ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ ($\sim$ 7% of SM expectation) simulated using gg2zz ME+Jimmy UE+Herwig PS+Tauola τ-lepton decays.

Monte Carlo Simulation: Backgrounds

Process	PDF	ME	UE	PS
Z + jets	CT10	PowhegBox	Pythia8	
$t\bar{t}$	CT10	MC@NLO	Jimmy	Herwig
$W^{\pm}Z$	CT10	PowhegBox	Pythia8	

- Various background processes simulated separately with different simulation programs (per table).

Event Selection: Electrons

- First selected by standard quality criteria:
  - Must be reconstructed in well-understood kinematic region:
    - $p_{\mathrm{T}} > 15$ GeV
    - $|\eta| < 2.47$
  - Must be reconstructed in a region without hardware problems.
- Standard set of identification criteria (loose$++$) applied, including requirements on:
  - Hits on track in various ID subsystems
  - Quality of track-cluster matching
  - Cluster shower shape (narrowness and penetration depth)

Event Selection: Muons

- First selected using a standard track selection:
  - Hits in multiple layers of both silicon tracking detectors.
  - Limits on sensors traversed without registering hits.
  - Successful extension of silicon track into TRT with many hits and few outliers within TRT acceptance.
- Must be reconstructed in well-understood kinematic region:
  - $p_{\mathrm{T}} > 15$ GeV
  - $|\eta| < 2.5$

Event Selection: Lepton Isolation & Impact Parameter

- Required to be isolated, nearby (with $\Delta R < 0.2$ w.r.t. the lepton ID track) activity required to satisfy:
  - Scalar sum momentum of all $p_{\mathrm{T}} > 1$ GeV tracks must be $< 15\%$ of the lepton p_{T}.
  - Scalar sum energy of all calorimeter cells must be $< 30\%$ of the lepton p_{T}.
- Required to originate at the PV, impact parameter required to satisfy:
  - d_0 of muons (electrons) within 3.5 (6) standard deviations of the unbiased PV[1]
  - z_0 within 2 mm of the unbiased PV

[1] primary vertex as reconstructed excluding the track whose impact parameter is being calculated

Event Selection

- Events only considered if no detector system had any problems.
- Events required to have reconstructed PV with ≥ 3 tracks.
- Lepton candidates selected in remaining events.
- Require exactly 4 leptons that form two opposite-sign, same-flavor pairs.
- Lepton pairs used to reconstruct Z-boson candidates.
- Resolve ambiguity in pairing for the $4e$ and 4μ channels by minimizing:
$$|m(Z1) - m^Z| + |m(Z2) - m^Z|$$
- Z candidates required to have invariant mass between 66 and 116 GeV.
- $\Rightarrow m_{ZZ}$ is always > 132 GeV by construction (avoiding overlap with the Higgs region).
- Events only accepted if a lepton from $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ decay satisfied trigger.

Background Estimation

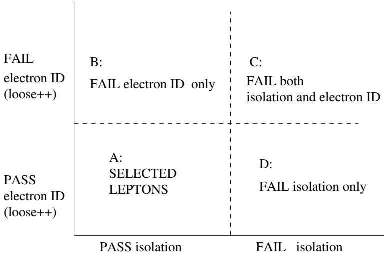
- Very little SM background production of 4 prompt leptons from vector boson decays.
- Background is from events with some prompt leptons (L) along with some number of lepton-like jets (J).
- J are objects mis-identified as leptons or leptons from non-prompt sources.
- This includes several SM processes that produce multiple prompt leptons in association with jets ($Z+$jets, $t\bar{t}$, $Z\gamma$, etc.).
- Estimated using the data-driven fake factor method.
- Simulated background samples only used to validate yields in and subtract prompt lepton contamination from the control regions used in the data-driven background estimation.

Background Estimation: Fake Factor Method

- Define control regions by inverting object selection for 1 and 2 objects.
- Measure pass:fail ratio, called the fake factor (FF), of selection criteria to be inverted in both Z+L and Z+J tagged samples, after subtracting contamination from $W^{\pm}Z$ and ZZ.
- Scale the yield in the 3 lepton+1 lepton-like jet (LLLJ) control region by FF to extrapolate into the signal region.
- Subtract the contamination from 2 lepton+2 lepton-like jet (LLJJ) events using the same FF.
- Subtract the contamination of both LLLJ and LLJJ regions by ZZ events using simulation (assign 10% normalization uncertainty).
- Therefore, the background is:

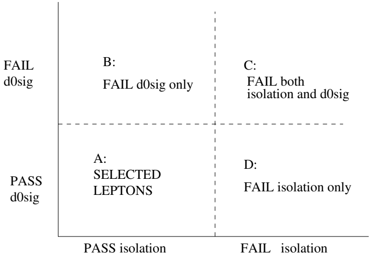
$$B = (N(LLLJ) - N_{ZZ}^{LLLJ}) \times FF - (N(LLJJ) - N_{ZZ}^{LLJJ}) \times FF^2$$

Background Estimation: Electron Fake Factor



- Electron fake factor is pass:fail ratio of loose++ and isolation requirements ($\frac{A}{B+D}$).
- Exclude events that fail both requirements to remain closer to signal region (region C).
- Region B allows for estimation of mis-identified hadrons.
- Region D allows for estimation of electrons from non-prompt sources.
- Use difference between measured and simulated fake-factors as the systematic uncertainty.

Background Estimation: Muon Fake Factor Definition



- Muon fake factor is pass:fail ratio of d_0-significance and isolation requirements ($\frac{A}{B+D}$).
- Exclude events that fail both requirements to remain closer to signal region (region C).
- Region B allows for estimation of muons from non-prompt sources (e.g. large angle b decays).
- Region D allows for estimation of mis-identified hadrons (i.e. hadronic punch-through).
- Use difference between measured and simulated fake-factors as the systematic uncertainty.

Background Estimation: Result

Item	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell'^+\ell'^-$
$(+)\ N_{LLLJ} \times FF$	1.0±0.4±0.3	0.6±0.6±0.4	1.8±0.9±1.0	3.4±1.2±1.7
from N_{LLLJ}	8	1	7	16
$(-) N_{LLJJ} \times FF^2$	0.1±0.1±0.1	0	0.2±0.1±0.1	0.3±0.1±0.2
from N_{LLJJ}	12	0	8	20
$(-) ZZ$ correction	0.3±0.1±0.1	0.5±0.1±0.4	1.0±0.1±0.6	1.9±0.1±1.1
Fake estimate, $N_{4\ell}^{\mathrm{fake}}$	0.6±0.4±0.2	$0.1^{+0.6}_{-0.1}\pm0.1$	$0.6^{+0.9}_{-0.6}\pm0.3$	1.3±1.2±0.5

- First uncertainty is statistical, second is systematic.
- Background estimate is smaller for muons than electrons.
- Total background is consistent with 0.

Systematic Uncertainties

- Determined uncertainties in simulation using independent measurements of various detector efficiencies and energy/momentum scales/resolutions.
- Reweighted simulated samples based on efficiency measurements and corrected energy/momentum scales/resolutions.
- Calculated changes in expected yield under variations of each correction by $\pm 1\sigma$ to get uncertainties in expectation.
- Determined uncertainty in background estimate to be the change in background yield based on uncertainties in the fake-factor (viz. statistics and background subtraction).

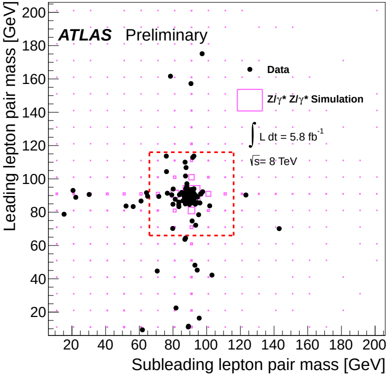
Systematic Uncertainties: Experimental

- Uncertainties in simulation (estimated using control studies in data).
- Electrons:
  - Energy scale: <0.1%
  - Energy resolution: 0.2%
  - Reconstruction efficiency: 1.2%
  - Identification efficiency: 1.8%
- Muons:
  - Momentum scale: <0.1%
  - ID Momentum resolution: 0.1%
  - MS Momentum resolution: <0.1%
  - Reconstruction efficiency: 0.6%
- Trigger efficiency: 0.2%
- Isolation/IP selection efficiency: 0.7% (0.5%) from electrons (muons)

Systematic Uncertainties: Theoretical

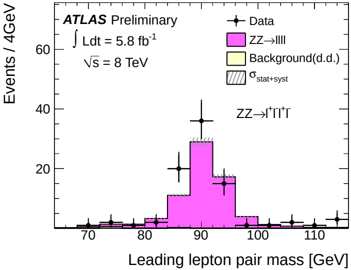
- Uncertainties in choices of theoretical parameters.
- PDF: 2.0%
  - Central values of acceptance and theoretical prediction calculated using CT10.
  - Uncertainties calculated using the 52 CT10 error eigenvectors and comparison to MSTW2008, calculated using MCFM.
- Renormalization and Factorization Scale: 0.2%
  - Central values calculated with both scales fixed at m_Z.
  - Uncertainties taken by varying the scales up and down by a factor of 2, calculated using MCFM.
- Parton Shower Effect: 1.0%
  - Evaluate the effect of parton shower on fiducial acceptance.
  - Uncertainties taken by comparing acceptance before and after the PYTHIA8 parton shower.

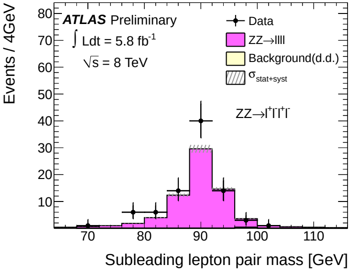
Kinematic Distributions: Z Mass Distribution



- Background is omitted from plot.
- Clear enhancement in red box that delimits signal region.

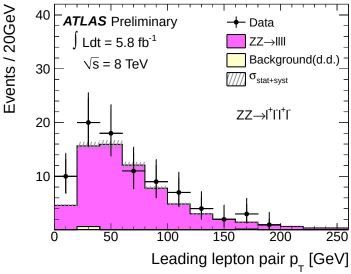
Kinematic Distributions: Z Mass

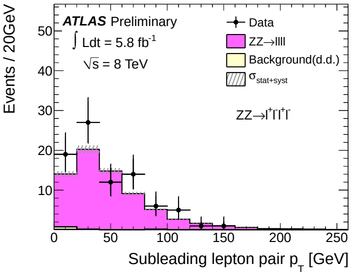




- Background in plots is a MC template scaled to the data-driven background estimate.
- Very small background, visible e.g. in the 96-100 GeV bin of the right (subleading Z) plot.
- Good agreement in Z line shape between data and MC.
- Leading and subleading Z both have normal line shape, as expected.

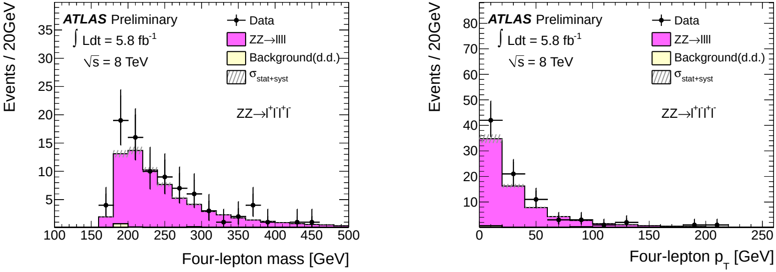
Kinematic Distributions: Z p_T





- Background in plots is a MC template scaled to the data-driven background estimate.
- Good agreement of both Z p_T spectra between data and MC.
- Distribution of leading Z p_T is harder than that of subleading Z p_T, as expected.

Kinematic Distributions: ZZ System Mass & p_T



- Background in plots is a MC template scaled to the data-driven background estimate.
- Good agreement in shapes of both distributions.

Observed Yields

Final state	$eeee$	$\mu\mu\mu\mu$	$ee\mu\mu$	combined ($\ell\ell\ell\ell$)
Observed	23	22	40	85
Expected Signal	16.5±0.8	20.9 ± 0.4	33.2 ± 0.9	70.5 ± 1.7
Background	0.6±0.4±0.2	$0.1^{+0.6}_{-0.1}\pm0.1$	$0.6^{+0.9}_{-0.6}\pm0.3$	1.3±1.2±0.5

- Results are consistent with expectation ($\sim 1.6\sigma$ upward fluctuation).

Cross Section: Fiducial Acceptance

- The expectation for the event yield in the signal region can be written as a function of the cross section (σ_{ZZ}), integrated luminosity ($\mathcal{L}$), branching fraction ($\mathcal{B}r(ZZ \to \ell^+\ell^-\ell'^+\ell'^-)$), fiducial acceptance ($A_{ZZ}$), detection efficiency (C_{ZZ}), and ratio of τ+X contribution to e and μ only contribution to signal (f_τ) as:

$$N = \mathcal{L} \times \sigma_{ZZ} \times \mathcal{B}r(ZZ \to \ell^+\ell^-\ell'^+\ell'^-) \times A_{ZZ} \times C_{ZZ} \times (1 + f_\tau) + N_{\mathrm{bkg}}$$

- The fiducial acceptance is defined as the fraction of events in the total phase space that fall within the fiducial volume:

$$A_{ZZ} = \frac{N^{\mathrm{MC\ Fiducial\ Volume}}_{\mathrm{Generated}\ ZZ \to \ell^+\ell^-\ell'^+\ell'^-}}{N^{\mathrm{MC\ Total\ Phase\ Space}}_{\mathrm{Generated}\ ZZ \to \ell^+\ell^-\ell'^+\ell'^-}}$$

- Fiducial volume is defined as the phase-space volume within which candidate events can be reconstructed:
  - Same invariant mass range for Z bosons (viz. 66-116 GeV)
  - All leptons required to have $p_{\mathrm{T}} > 15$ GeV
  - All leptons required to have $|\eta| < 2.5$
  - $\Delta R(\ell, \ell') > 0.2$ for all pairs of charged leptons
- Using MCFM in the $e^+e^-\mu^+\mu^-$ channel, calculate that:

$$A_{ZZ} = 0.500 \pm 0.001 \pm 0.012$$

- Assume A_{ZZ} to be the same in the $e^+e^-e^+e^-$ and $\mu^+\mu^-\mu^+\mu^-$ channels by lepton universality.

Cross Section: Detection Efficiency

Channel	C_{ZZ}
$e^+e^-e^+e^-$	0.61±0.01±0.03
$\mu^+\mu^-\mu^+\mu^-$	0.77±0.01±0.02
$e^+e^-\mu^+\mu^-$	0.68±0.01±0.02
$\ell^+\ell^-\ell'^+\ell'^-$	0.69±0.01±0.02

- The detection efficiency is calculated from simulation as the ratio of the expected signal yield to the generated yield in the fiducial volume:

$$C_{ZZ} = \frac{N^{\mathrm{MC}}\,(\text{Signal Region}) \times \mathrm{SF}}{N^{\mathrm{MC}}\,(\text{Fiducial Volume})} \tag{1}$$

- SF is combined effect of all efficiency corrections used for systematic uncertainty estimation.
- Muons have higher reconstruction efficiency than electrons.
- Combined $\ell^+\ell^-\ell'^+\ell'^-$ channel has $\sim$same efficiency as the $e^+e^-\mu^+\mu^-$ channel.

Cross Section: Likelihood Function

- Poisson probability to observe N^i_{obs} events given expectation of N^i_{exp} is:

$$P\left(N^i_{\text{obs}}; N^i_{\text{exp}}\right) = \frac{\left(N^i_{\text{exp}}\right)^{N^i_{\text{obs}}} \cdot e^{-N^i_{\text{exp}}}}{N^i_{\text{obs}}!}. \tag{2}$$

- For a given N^i_{obs} this can be interpreted as a likelihood function.
- Define measured cross section as value that maximizes likelihood function.

Cross Section: Systematic Uncertainties

- Use Gaussian nuisance parameters for systematic uncertainties, defining set of variables $\{x_k\}$ constrained in likelihood function as:

$$L\left(\sigma_{ZZ}, \{x_k\}\right) = \prod_{i=1}^{3} \left(\frac{\left(N^i_{\text{exp}}\left(\sigma_{ZZ}, \{x_k\}\right)\right)^{N^i_{\text{obs}}} \cdot e^{-N^i_{\text{exp}}\left(\sigma_{ZZ}, \{x_k\}\right)}}{N^i_{\text{obs}}!} \right) \times \prod_{k=1}^{n} \left(e^{-\frac{x_k^2}{2}} \right). \quad (3)$$

- Here N^i_{exp} is as aforementioned and i represents lepton flavor channel.
- Defining variation in expected signal and background yields due to k^{th} uncertainty source as $\left\{S^i_k\right\}$ and $\left\{B^i_k\right\}$, expected signal and background yields as a function of the $\{x_k\}$ becomes:

$$N^i_{\text{sig}}\left(\{x_k\}\right) = N^i_{\text{sig}}(0) \times \left[1 + \sum_{k=1}^{n} \left(x_k \cdot S^i_k\right)\right], \quad (4)$$

$$N^i_{\text{bkg}}\left(\{x_k\}\right) = N^i_{\text{bkg}}(0) \times \left[1 + \sum_{k=1}^{n} \left(x_k \cdot B^i_k\right)\right]. \quad (5)$$

- These nuisance-dependent yields sum to the N^i_{exp} in the likelihood function.

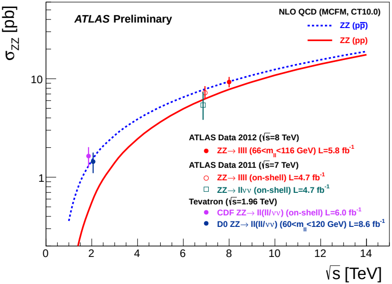
Cross Section: Fit

- The likelihood function is maximized using the MINUIT program.
- Systematic uncertainties are determined by shifting each nuisance until ln L shifts by 0.5 and recalculating the cross section.
- Measured cross section both in the fiducial volume (i.e. fitting $\sigma_{ZZ} \times \mathcal{B}r(ZZ \to \ell^+\ell^-\ell'^+\ell'^-) \times A_{ZZ}$) and the total phase space (i.e. fitting only σ_{ZZ}) as:

	Fiducial Cross Section
Measured	$21.01^{+2.40}_{-2.23}(\text{stat.})^{+0.59}_{-0.49}(\text{syst.}) \pm 0.76(\text{lumi.})$ fb
SM Prediction	$16.75^{+0.95}_{-1.02}$ fb
	Total Cross Section
Measured	$9.26^{+1.06}_{-0.98}(\text{stat.})^{+0.36}_{-0.30}(\text{syst.}) \pm 0.33(\text{lumi.})$ pb
SM Prediction	$7.41^{+0.40}_{-0.36}$ pb

- Measured results in agreement with the SM expectations.

Conclusion



- Measured cross section of ZZ production in the $\ell^+\ell^-\ell'^+\ell'^-$ channel at 8 TeV.
- Measured in the 66-116 GeV Z-candidate invariant mass range (near the Z pole).
- Result is consistent with SM prediction ($\sim$1.6σ upward fluctuation).
- Intend to present updated result with full 2012 8 TeV dataset ($\sim$20 fb^{-1}) at Moriond.

Questions?

Data & MC Samples

- All data and MC used in the W/Z physics ntuple D3PD format (called NTUP_SMWZ)
- All datasets processed through standard ATLAS reconstruction, through the centrally managed production system
- Using the standard AllGood_v3 GRL, which requires all data quality metrics except τ-tagging quality to be evaluated as good
- Using data sample as frozen for ICHEP (a total of 5.8 fb^{-1}), except modified to remove $\sim$ 10 lumiblocks for which nutple production failed